NASA CR-72292
SKF AL67T063

EXTREME TEMPERATURE AEROSPACE BEARING-LUBRICATION SYSTEMS

by

L. B. Sibley and L. A. Peacock

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS3-7912
TASK ORDER NO. 2

RESEARCH LABORATORY
SKF INDUSTRIES, INC.
ENGINEERING AND RESEARCH CENTER
KING OF PRUSSIA, PA.

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May 20, 1967

CONTRACT NAS3-7912

Project Management
NASA Lewis Research Center
Cleveland, Ohio
Air-Breathing Engine Division
Dennis P. Townsend, Project Manager
Erwin V. Zaretsky, Research Advisor

RESEARCH LABORATORY
SKF INDUSTRIES, INC.
ENGINEERING AND RESEARCH CENTER
KING OF PRUSSIA, PA.

ACKNOWLEDGEMENT

Contributions to this program of the following members of the SKF Industries, Inc., Research Staff are acknowledged: G. Chiccarine, R. Evan, D. Hahn, J. Kozol, H. Mahncke, R. Pilkington W. Rhoads, C. Wachendorfer, and A. Thomson.

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ABSTRACT

Angular-contact ball bearings (25-mm bore, 205-size) made with vacuum-melted WB-49 tool steel rings and M-1 steel balls and cages have been tested at 600°F, 43,000 rpm, and 459 lbs. thrust load with Mobil XRM-177F hydrocarbon lubricant (containing an anti-wear additive) using a low oxygen environment. No flaking fatigue failures occurred in a group of 30 such bearings tested to twice the AFBMA-computed L_{10} life. Three bearings in this group failed by smearing at lives giving an estimated L_{10} life of 1.4 times the AFBMA-computed L_{10}, indicating that adequate lubrication under these extreme conditions is possible and that no reduction in bearing design life is required. Also evident, however, was the fact that smearing failures are to be anticipated in operation at these extreme conditions and that design solutions capable of reducing their incidence will further enhance bearing reliability in service.

A black-oxide coating commonly used on aerospace bearing surfaces to improve bearing performance under marginal lubrication conditions was found to attack the surfaces of WB-49 steel rings excessively, causing a drastic reduction in life, therefore, uncoated bearings were used in the above test group.

A lot of M-50 tool steel bearings was manufactured for use on subsequent Tasks.

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by L. B. Sibley and L. A. Peacock

SKF Industries, Inc.

FOREWORD

This is the Final Summary Report submitted in fulfillment of Task Order No. 2 under NASA Contract No. NAS3-7912 entitled "A Study of Extreme Temperature Aerospace Bearing Lubrication Systems". It encompasses research conducted from November 22, 1965 through April 30, 1967 and previously reported in Monthly Progress Reports No. 1 to 18.

SUMMARY

A group of 30 angular-contact 25-mm bore ball bearings made of vacuum-melted high-temperature tool steels were life tested successfully at 600°F outer-ring temperature with a synthetic hydrocarbon lubricant having an anti-wear additive. The tests were conducted on 2 bearings at a time in SKF Industries' test rigs simulating typical high-speed aerospace auxiliary drive spindles. The rigs have labyrinth seals and were inert gas blanketed to provide an oxygen content of less than one percent in the atmosphere over the lubricant.

The inner and outer rings of the 205-size test bearings (SKF 7205 VAR) were made of consumable-electrode vacuum melted (CVM) WB49 tool steel and the balls of CVM M-1 tool steel. These steels have hot hardness and stability characteristics making them suitable bearing ring and ball materials up to temperatures of 1000°F and 800°F, respectively. The cages in these bearings were made of silver-plated M-1 steel with extra wide guide land surfaces. The nominal contact angle of the test bearings was 19°, the nominal inner-ring ball-groove conformity was 52.4% and the nominal outer-ring conformity was 53.2%, with the rings finished to a cross-groove roughness of less than 4 microinches, rms. All bearings were tested with Mobil XRM-177F lubricant circulated at a nominal 400 cc/min through each bearing at 43,000 rpm shaft speed under 459 lbs. thrust load, correspond-

ing to a maximum computed Hertz contact stress of 253,000 psi (on the outer ring) and an AFBMA-computed bearing L_{10} life = 93 hours or 240 million inner-ring revs. (56 hours, or 144.5 mill. revs. accounting for changes in contact angle due to the mounting fits used and the centrifugal and gyroscopic forces on the balls, which are neglected in AFBMA life computations).

No failures occurred from fatigue spalling of the balls or ring tracks in the 30 bearings tested under the above conditions to a time-up life of 180 hours (464 mill. revs.). Three bearings failed by smearing (gross metal transfer on the balls and grooves due to lubrication-related thermal instabilities) at lives of 18 to 48.9 hours (47 and 126 mill. revs.). A maximum likelihood estimated bearing life for the smearing failures is L_{10} = 127 hours (328 mill. revs.). These results indicate fully adequate reliability of this bearing-lubricant combination under these test conditions, compared to AFBMA standards, with the possibility of further life increases by further improving the lubrication and functional characteristics of the bearings and test system since no limiting fatigue failures of the bearing steel occurred in the present tests.

Another group of 14 bearings were tested in a manner similar in all respects to those described above, except that the test bearings (SKF 7205 VAK) were treated with a black-oxide surface coating known to reduce lubrication-related failures of bearings made of 52100 or M-50 type bearing steels. All of these tests were terminated by smearing or lubrication-related spalling failure at lives of 0.2 to 9.3 hours (0.5 and 24 mill. revs.). This drastic reduction in life from that obtained with the uncoated 7205 VAR bearings is attributed to selective chemical attack of the black-oxide coating process on the WB-49 steel producing, by differential etching according to material "fiber flow", a "washboard" groove surface on the metal under the coating.

A new lot of 54 bearings made of CVM M-50 tool steel (SKF 7205 VAP) was manufactured for use in subsequent testing on this program and 146 semifinished ring sets from the same lot are being held for finishing at some future date when required.

INTRODUCTION

Aerospace turbine power equipment requires shaft support systems capable of reliable operation at high speeds with substantial, often reversing, thrust loads, and for high efficiency, with as high operating temperature as possible. Angular-contact ball bearings are commonly used in aerospace systems and the maximum temperature capabilities of conventional bearings and lubricants often are the limiting factors in developing advanced turbine equipment having improved reliability and efficiency.

In previous research studies on the operation of high-speed high-temperature ball bearings (1-9)*, there has been some success in obtaining long-term satisfactory bearing operation at temperatures of 450-500°F and higher, usually under relatively light loads, using high-temperature alloy or tool steel bearings and thermally stable synthetic lubricating fluids or sometimes solid lubricants. These studies generally indicated that ball bearings operating at these temperatures would probably have to be derated substantially in load-carrying capacity from that obtained with conventional lubrication at ordinary temperatures (3, 5, 6). Some studies have indicated, however, that with the proper combination of bearing material, design and lubrication, operation at 500°F and 600°F can be achieved with as long life and perhaps as high reliability as at lower temperature (8-12).

In one of these previous studies (8, 9), the development of the bearing-lubricant test facility used in the present research is described. It was shown in this previous program that the limiting temperature of a wide variety of candidate lubricating fluids (suitably inerted, if vulnerable to oxidation) varies generally as the viscosity, a minimum viscosity of 1 to 1.5cs being required at the bearing operating temperature to avoid excessive lubrication distress under the test conditions used. Bearings tested with lubricants having less viscosity than this at the bearing operating temperature suffered a glazing and superficial pitting type of surface distress in the ball tracks which resulted in a greatly reduced life to spalling failure of the bearing. These viscosity effects are attributed to the formation of elastohydrodynamic (EHD) films at the ball-race

*Numbers in parentheses refer to References at the end of this report.

contacts which, when these films become too thin compared to the composite bearing surface roughness, results in intimate surface contact and asperity interaction manifested as the above-described surface distress. Thus EHD theory can be used to extrapolate these results to other bearing sizes and operating conditions (13-15).

Bearing design principles and testing procedures were developed in this previous program (8, 9) which culminated in the high-temperature high-speed life testing of groups of bearings made of consumable-electrode vacuum melted (CVM) M-1 tool steel using the most promising candidate lubricant from each of the three categories of hydrocarbon, ester and polyphenyl ether base-stocks, respectively. Thirty bearings tested with the ester-base candidate, Esso Turbo Oil 35, at 500°F resulted predominantly in lubrication-related fatigue spalling failures, of the type described above, at lives giving an estimated bearing life of ¼ to ½ of the AFBMA-computed life for conventional lubrication conditions. Hard coke deposits were formed with this ester lubricant even though inert gas blanketed in the tests. Similar testing at 600°F with the polyphenyl ether candidate, Monsanto Skylube 600, however, resulted predominantly in early bearing smearing failures which are characteristically different from the glazing and early spalling failures described above. Smearing failures, which are observed as gross metal transfer and galling of all the rolling surfaces in the bearing, apparently result from thermal instabilities of the bearing-lubricant combination, to be described in more detail later in this report.

Similar early smearing failures occurred with the hydrocarbon candidate, Mobil XRM 109F, which is additive-free. However, 10 bearings tested with Mobil XRM 177F lubricant, which is the XRM 109F base-stock with an anti-wear additive, ran without any kind of failure at 600°F to lives over 3 times the AFBMA-computed life, indicating that high bearing life and reliability are indeed feasible at these temperatures if lubrication-related bearing failures can be eliminated.

It is the purpose of the present program to extend these earlier results to other bearing steels and lubricants and to test sufficient numbers of bearings to establish reliability and life parameters for aerospace bearing-lubricant system design purposes. In the Task reported here, groups of bearings having

CVM WB-49 tool steel rings and CVM M-1 balls were tested at 600°F with Mobil XRM 177F lubricant. Also, CVM M-50 tool steel bearings were manufactured for use on subsequent Tasks on this program.

TEST RIGS

Three high-temperature high-speed bearing test machines developed by SKF Industries, Inc., and fitted with constant speed 43,000 rpm drives for endurance testing, were used on this Task. A layout sketch of this rig is shown in Enclosure 1 and its design and operation are described in detail in (8, 9). Essentially, each rig tests two 7205 angular-contact ball bearings mounted on the same shaft and thrust loaded against each other by a dead weight and lever system. Screw pumps machined in the shaft between the two test bearings circulate the test lubricant from a 2000 cc sump through the bearings and back to the sump through sight-flow tubes used as a visual check on the lubricant flow through the bearings. Nitrogen gas is supplied as an inert blanket over the oil in the sump and to both ends of the test bearing housing. Mass spectrometer analysis of the atmosphere in one rig during a typical test indicated an oxygen content of 0.96%. Lubricant is replenished periodically to the sump as it is lost by evaporation and by slight leakage through the labyrinth seal on the drive end of the shaft.

Each rig is driven through a speed-increaser gearbox and quill coupling by a 60 horsepower induction motor and is located with its drive in an explosion-proof test cell. Overall views of one test rig in its test cell and its control cabinet located outside the cell are shown in Enclosures 2 and 3, respectively. Test bearing and oil temperatures are maintained by electrical cartridge-heaters in the rig housing and sump walls, the heaters being controlled by time-proportioning on-off temperature controllers. Temperature fluctuations are evened out by the relatively massive steel sections in which the heaters are imbedded. At the high bearing thrust loads and speeds used for endurance testing, however, the test bearings themselves generate almost enough heat to maintain the rig temperature at 500°F to 600°F, so that fan cooling of the housing is employed to the degree necessary to maintain some heater input power for temperature control purposes.

TEST BEARINGS

The rings and balls of the test bearings for this program were manufactured from aircraft bearing quality (CVM) tool steels having the most promising fatigue life, high-temperature stability and long-term hot hardness characteristics. Based on the available data on these properties reviewed in (8, 9), CVM M-1, CVM WB49 and CVM M-50 steels were selected. The composition and estimated maximum useful temperature of these bearing steels are given in Enclosure 4. The design and specifications of the 7205 VAK and 7205 VAR test bearings having WB49 steel rings and M-1 steel balls, which were used in the tests reported here, are given in Enclosures 5 and 6, respectively. Enclosure 7 shows similar specification data for the 7205 VAP bearings having M-50 steel rings and balls, which were manufactured on this Task for use in future Tasks.

The cages used in all test bearings were made of M-1 steel tempered to a hardness of Rc 57 to 60 and electroplated with silver to a thickness of 0.001" to 0.002". This cage material, and the designs shown in Enclosures 8 and 9 for the bearings having counter-bored outer and inner rings, respectively, are based on the results of previous studies (8, 16) indicating superior performance under extreme lubrication conditions.

The inner and outer rings of both the 7205 VAK and 7205 VAR bearings were made from the same heat of CVM WB49 steel and were manufactured in the same lot, except the 7205 VAK inner rings, which were reworked from 7205 VAR inner rings. The balls in the VAK bearings were from one heat and those in the VAR bearings from another heat of CVM M-1 steel. The rings and balls in the 7205 VAP bearings were all made from the same heat of CVM M-50 steel. The analysis of each lot of steel obtained for test bearings was checked and found within the limits given in Enclosure 4. Steel samples from each heat treatment lot were checked metallurgically for proper structure and hardness as listed in Enclosure 10.

Dimensional measurements before testing on all bearings made for this Task are given in Enclosures 11 and 12. All the 7205 VAK and 7205 VAR bearings listed in Enclosure 11 were tested in this Task as reported herein. The 54 bearings of the 7205 VAP design listed in Enclosure 12 are for use on a subsequent Task. During the course of making the 7205 VAP bearings, 146 additional ring sets were manufactured which do not meet the dimensional requirements of the 7205 VAP design and are therefore stored in a semi-finished condition to be reworked later either to the 7205 VAP design or a modified design, as may be decided from the results of subsequent testing.

TEST LUBRICANT

A sufficient quantity of Mobil XRM 177F lubricant was obtained to complete all tests on this program from the same lot of lubricant. This lot is not the same as that used previously for early screening tests of the XRM 109F base-stock reported in (8), but it is the same as that used in later endurance testing (8, 9) and in other tests of larger jet-engine mainshaft size bearings (10, 17). Typical properties data for this lubricant lot are given in Enclosure 13 including a comparison of properties with previous lots of the same lubricant.

TEST PROCEDURE

The standard procedure used for conducting the bearing-lubricant endurance tests reported here is as follows:

1. The rig is assembled with the test bearings and the initial charge of test lubricant in the sump, the load is applied, all valves in the oil lines are closed except the inboard bearing drain valves which are set at one turn open (the specified setting for 43,000 rpm operation) and the nitrogen blanket gas flow is started over the oil in the sump.

2. The rig is preheated for about an hour with both the housing and sump heater controllers set at 300°F.

3. The rig is started by first increasing the nitrogen flow to the sump wide open and closing the sump vents to prime the screw pumps on the test shaft, and when oil starts to flow-out the drive-end labyrinth seal with the shaft rotated slowly by hand, then the sight-glass outboard drain valves and sump vent lines are opened simultaneously with starting the drive motor. Then the nitrogen flow to the sump is reset to the preheat level, the nitrogen flow lines to the housing cavities are opened, the sump heaters are turned off and the housing heater controller is set to the test temperature of 600°F.

4. The test bearing outer-ring temperatures are montiored every 6 minutes by the central data collection system described in (8) and as the test temperature is approached either one or two cooling fans are turned on. The position and number of fans is determined by "cut-and-try" during the first hour of running, the final fan placement being selected to provide a sump temperature cooler than the bearings and to leave some power input to the housing heaters for bearing temperature control.

5. Test lubricant lost by evaporation and seal leakage is replenished to the sump during each test at a rate of about 25cc per hour. Automatic shutdown of the rig occurs if the oil pressure from either screw pump decreases below a preset limit of 30% of the normal oil pressure or if a vibration-sensitive switch fastened to the load lever arm detects an abrupt increase in rig vibration level. The rig is disassembled for inspection of the test bearings if manual rotation of the shaft with the bearings under load indicates any unusual roughness in the bearings. Testing of both bearings is suspended when either test bearing shows evidence of fatigue spalling, smearing, or lubrication distress in the form of glazing and superficial pitting to such an extent that the bearing is judged inoperable (8, 15).

TEST RESULTS

Tests were started with black-oxide coated WB-49 steel 7205 VAK bearings. One of the two bearings in each test of the first 10 bearings tested smeared at lives ranging from 1.0 to 9.3 hours (2.6 to 23.9 mill. revs.), with each smearing failure accompanied by severe cage wear. This led to the hypothesis that insufficient cage pocket clearance for the oversize balls used in these bearings caused the observed failures. Four additional 7205 VAK bearings having oversize cage pockets were tested and produced similar results thereby contradicting the above hypothesis. Two more 7205 VAK bearings having oversize cage pockets were tested at 400°F with Esso Turbo Oil 35 which is known to have good boundary lubricating properties at this temperature and also produced an early smearing failure. A typical 7205 VAK smearing failure is shown on Enclosure 14 and the life data obtained with these 7205 VAK bearings are summarized in Enclosure 15. Maximum likelihood life analysis of the 14 bearings tested in XRM 177F lubricant indicated L_{10} = 0.4 hours (1.1 mill. revs.) for these smearing failures.

In order to determine if any flaws had developed in the test machines or the test operating procedures two previously tested (8, 9) M-1 steel bearings (accumulated life of 254 hours at 600°F with XRM 177F without failure) were remounted and run an additional 9 hours at 600°F with XRM 177F with no sign of bearing failure. Consequently a thorough examination was made of all bearings tested to date on this program, as well as some selected bearings from the previous program (8, 9) and bearing parts in various stages of manufacture. This study revealed that the microscopic roughness pattern due to etching attack by the black-oxide coating bath on the steel grain structure was much more pronounced in the tracks of the recently tested WB-49 steel rings than in the tracks of previously tested M-1 steel rings, and that this pattern could be found underneath the black oxide coating on WB-49 steel 7205 VAK bearings, but not on uncoated WB-49 steel 7205 VAR bearings as shown by Enclosures 16 and 17, respectively. No significant attack of M-50 steel was found under the black oxide coating, as shown in Enclosure 18.

Two WB-49 steel 7205 VAR bearings that had not been black oxide coated, and having a design unlike the 7205 VAK, but essentially the same as the 456684 bearings tested in (8, 9), were then tested at 600°F with XRM 177F oil. After these two bearings had accumulated 38 hours running time without failure, additional uncoated 7205 VAR bearings were tested under the same test conditions. In all, thirty 7205 VAR bearings were tested (15 tests), as summarized in Enclosure 19. Of the fifteen tests, twelve tests (24 bearings) reached their time-up life of 180 hours (462.2 mill. revs.) without any failures. In three other tests involving 6 bearings, one of the two mating bearings in each test suffered a smearing failure at lives ranging from 18.0 to 48.9 hours (46.2 to 125.6 mill. revs.). In all instances the unfailed bearings appeared to be in good condition except for some fragment denting in the raceway grooves and a slight degree of cage bore wear (less than 0.1 mill. to 4.5 mills.). The typical appearance of the failed and unfailed 7205 VAR bearings is shown in Enclosures 20 and 21, respectively. The failure data for the 7205 VAR bearings were analyzed by the maximum likelihood life estimation technique (8), giving an estimated L_{10} = 127 hours (328 mill. revs.) for these smearing failures. The estimated life characteristics of this group are plotted on the Weibull graph in Enclosure 22, together with points representing the pairs of bearings tested, plotted according to the method of Schreiber (18).

The test rigs were relatively free of deposits after these tests except for some coking on the outside of the housings where test oil spilled out of the labyrinth seal or through thermocouple glands and also some black solids in the oil in the bottom of the sump. Analysis of the oil from a similar previous 600°F test (8) indicated a significant degradation of the oil after a 280-hour test at 600°F, as shown in Enclosure 25.

DISCUSSION

The beneficial effect of black oxide coating on AISI 52100 steel bearings has been demonstrated (19) where the presence of the coating was shown to reduce substantially the loss in bearing life due to lubrication distress suffered by uncoated bearings. In a recent program in the SKF Industries, Inc. Laboratory black oxide coated and uncoated M-50 tool steel bearings were endurance tested with fully adequate lubrication and no significant difference in life was detected, indicating no adverse reaction of the black oxide coating bath with M-50 steel. The tests reported here, however, have suffered early failure because the black oxide coating bath reacts by differential etching in a detrimental way with WB-49 tool steel bearing surfaces to cause a severe reduction in bearing life even under lubrication conditions giving little or no loss in life of comparable uncoated WB-49 bearings.

A probably explanation for the attack on WB-49 steel by black oxide coating chemicals is given in Enclosure 23 which shows typical metallographic structures of WB-49 steel bearings on which endurance life data are reported in (8). The metallographs indicate a significant amount of carbide banding which has not (8) caused loss in endurance life. Such banding is encountered frequently in tool steel due to the high carbide content. Even though this banding apparently does not affect bearing fatigue life of tool steels, it does affect the nature of the surface finish that can be obtained and apparently also leads to differential etching of WB-49 surfaces in chemical treatments such as black oxide coating.

The expected life of the bearings tested on this Task can be computed (see (8), Appendix I) according to the AFBMA (Anti-Friction Bearing Manufacturers Association) method (20). The life thus calculated for which 90% of the bearings are expected to survive without fatigue spalling of the ball-race contacts is L_{10} = 93 hours (240 mill. revs.). However, since significant centrifugal and gyroscopic forces exist on the balls in the bearings under the high-speed test conditions, and since unusual mounting fits were used on the shaft and housing in these tests to control the bearing internal clearance over the wide range of operating temperatures used, none of which effects are accounted for in the AFBMA method of calculation, computer-estimated life and operating parameters were calculated according to

Appendix I in (8) which take these effects into account and are given in Enclosure 24. From these calculations, the 7205 VAR bearing has an expected life of L_{10} = 56 hours (144.5 mill. revs.) for fatigue spalling failure, using the Lundberg-Palmgren material constants for standard bearing steel. For both 6309 and mainshaft size ball bearings made of vacuum-melted tool steels, an average life-increase factor of 8.5 has been demonstrated in endurance tests with fully adequate lubrication at SKF Industries, Inc., and elsewhere (12), and a life-increase factor of five is commonly used in the conservative design of tool-steel jet-engine mainshaft bearings. It is debatable whether similar life increase factors are justified for the smaller 7205 bearings operating at 600°F where the lubricant film thickness/roughness ratio is less than for current mainshaft bearings, but a material life-increase factor of about five can be expected.

The expected fatigue life of the present bearings is L_{10} = 280 hours (723 mill. revs.), assuming five times the computer-estimated life. The fact that 30 bearings were tested to a time-up life of 180 hours (464 mill. revs.) with no incidence of fatigue spalling failure (only three <u>smearing</u> failures) demonstrates a life-increase factor of at least three for these bearings and indicates that very little if any reduction factor for bearing <u>fatigue</u> life is necessary for 600°F operation of WB-49 bearings, as long as adequate lubrication is provided. A summary of all endurance data from this program and those reported in (8) is given in Enclosure 26, as further evidence supporting the above conclusion.

The bearing smearing failures in the tests reported here have no relation to bearing fatigue spalling. The most likely mechanism of these smearing failures is the self-aggravating loss of bearing clearance due to thermal instabilities and related localized breakdown of boundary lubrication in these high-speed bearings. Heat generation in a thrust-loaded angular-contact ball bearing is concentrated on the inner race and varies with the spinning friction at the ball-inner race contacts (8). It is desirable to minimize this spinning heat generation by making the nominal bearing contact angle as small as possible. However, momentary increases in spinning heat generation can occur and tend to increase the inner ring and ball temperatures above the outer ring temperature, which decreases the bearing clearance and local contact angle at least for the ball in question, causing a greater proportion of the total thrust load to be carried by that ball, thus increasing the local heat generation and causing a "snow balling" effect that ends in smearing and seizure of the bearing.

The drastic increase in the frequency of smearing failures with the roughening of the WB-49 bearing surfaces caused by reaction with the black-oxide coating bath indicates the sensitivity of high-speed bearing thermal balance to lubrication surface effects. For this reason, future Tasks on this program will be devoted to exploring the EHD film conditions which exist at high speeds and temperatures in order to guide the development of improved lubricants and bearing design concepts.

CONCLUSIONS

1. No reduction factor for the fatique life of ball bearings having WB-49 rings at 600°F is required below that used for vacuum-melted tool steel bearings at lower temperatures is adequate lubrication is provided.

2. Some smearing failures occur in angular-contact WB-49 bearings tested at 600°F under high thrust load and high speed with Mobil XRM 177F lubricant, but these failures occur sufficiently late in life and with a low enough incidence rate to permit reliable bearing operation to at least the AFBMA-computed life.

3. Inerting the bearing-lubricant system at 600°F to somewhat less than one percent oxygen content permits satisfactory circulation of the XRM 177F synthetic hydrocarbon lubricant without excess sludge accumulation, but significant fluid degradation still occurs over long (280 hours) periods.

4. A black-oxide coating used successfully to improve the performance of 52100 and M-50 steel bearings operating under marginal lubrication conditions was found to attack WB-49 steel bearing surfaces differentially and has significantly reduced the resistance of such bearings to smearing failure at high speeds and temperature.

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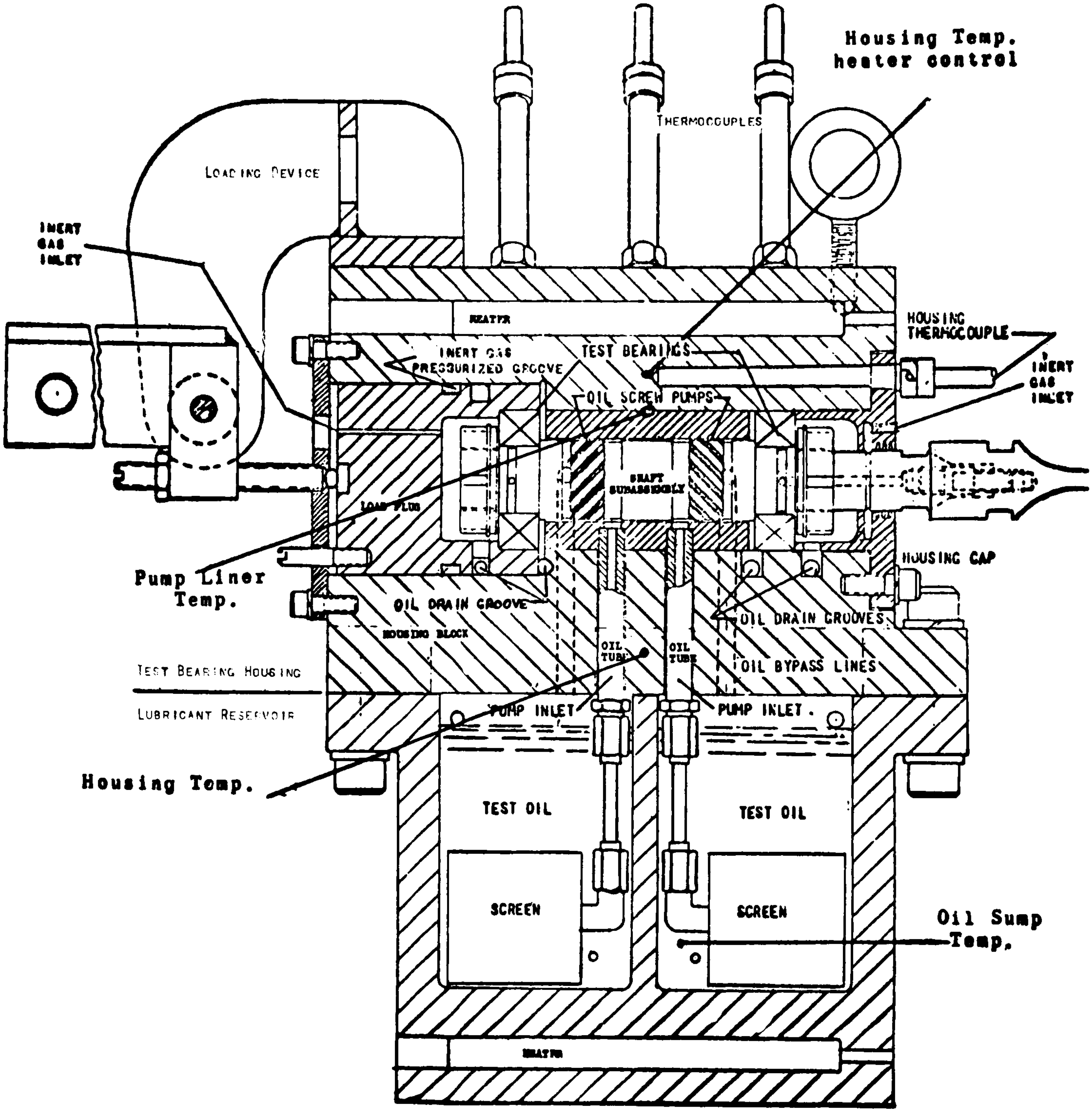
19. Lawrence, J. C., Schmidt, W. E., "Radioisotope Technique Applied to the Investigation of Surface Contact in Rolling Element Bearings", ASLE Trans., 5 321-34 (1962).

20. AFBMA Standards, "Methods of Evaluating Load Ratings for Ball Bearings", Section No. 9, The Anti-Friction Bearing Manufacturers Association, Inc., 60 East 42nd Street, New York 17, New York.

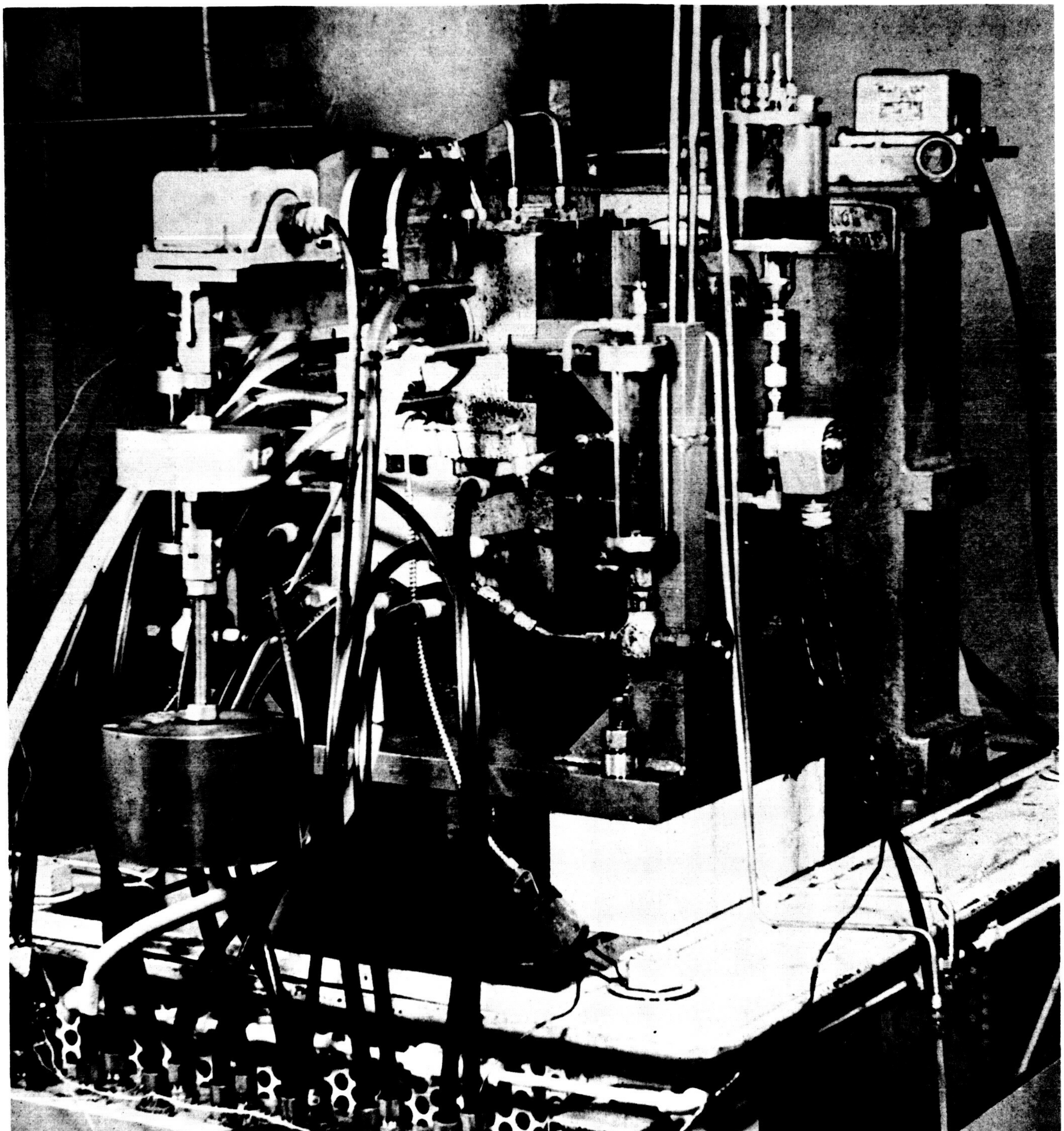
ENCLOSURE 1

LAYOUT SKETCH OF HIGH-SPEED HIGH-TEMPERATURE TEST RIG



ENCLOSURE 2

HIGH-SPEED HIGH-TEMPERATURE BEARING TEST MACHINE



ENCLOSURE 3

TEST RIG CONTROL PANEL

Oil Reservoir
and Housing
Temp. Control

Hour Meter

Motor and
Heater On-
Off Switches

Instrumentation
Switches

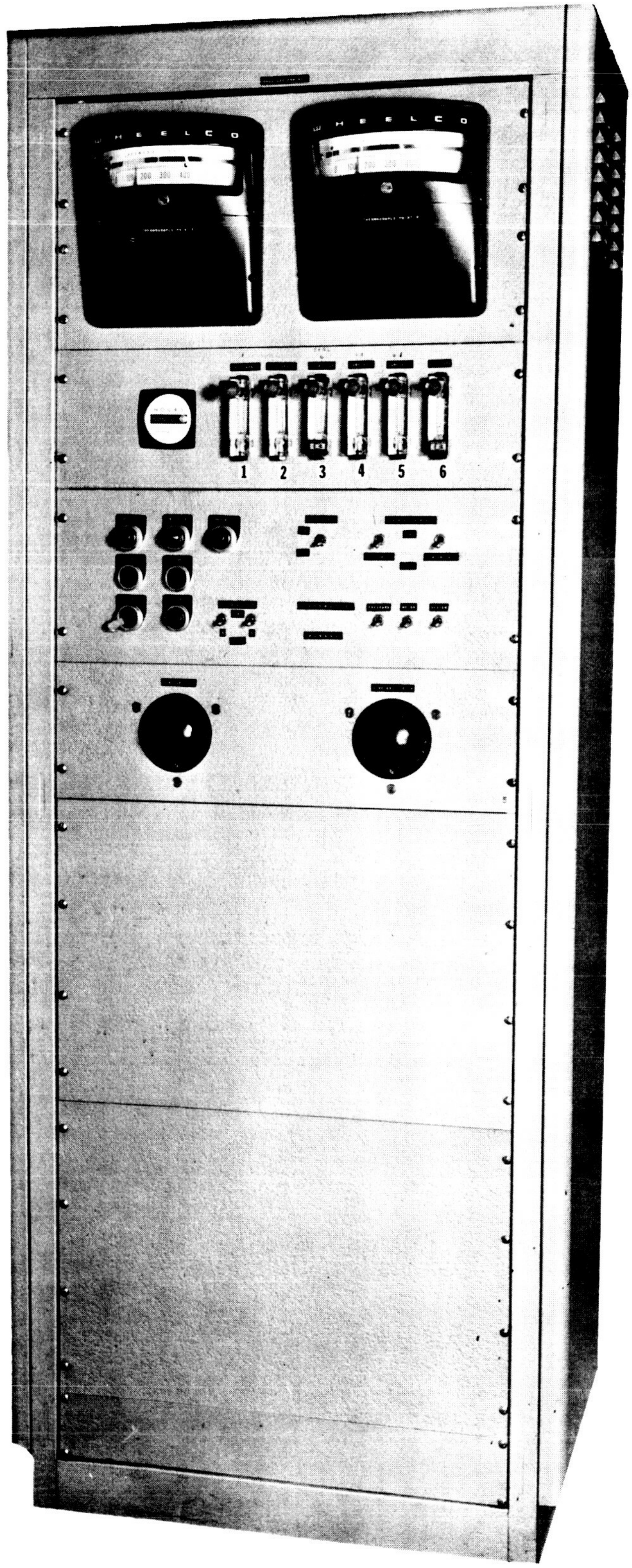
Fine Adjust-
ment Heaters

6-7 13-14

N_2 Purge Meters

Heater Switches

Automatic
Shut Offs



CONSTANT SPEED RIG

ENCLOSURE 4

COMPOSITION AND LIMITING TEMPERATURE OF HIGH TEMPERATURE BEARING STEELS

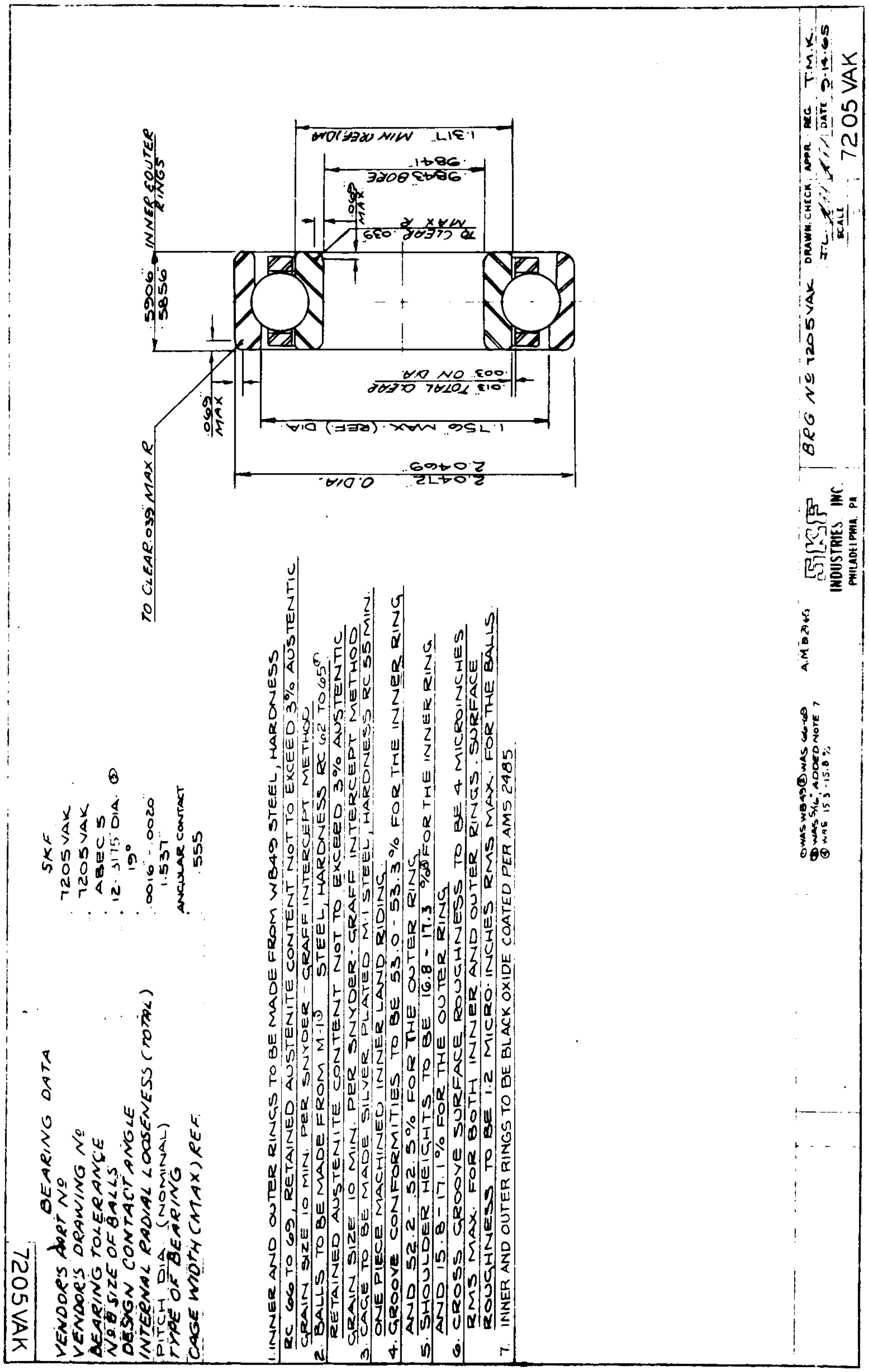
Element	M-50	M-1	WB-49
C	.77-.85	.75-.85	1.00-1.10
Mn	0.35 max.	0.15-0.40	0.20-0.40
Si	0.25 max.	0.15-0.40	0.20-0.40
Cr	3.75-4.25	3.5-4.25	4.00-4.50
P	0.015 max.	0.015 max.	0.015 max.
S	0.015 max.	0.015 max.	0.015 max.
Ni	0.10 max.	0.10 max.	0.10 max.
Cu	0.10 max.	0.10 max.	0.10 max.
Mo	4.00-4.50	8.45-9.25	3.50-4.00
W	0.25 max.	1.40-2.00	6.50-7.00
V	0.90-1.10	1.00-1.20	1.80-2.10
Co	0.25 max.	-	5.00-5.55
Maximum Useful Temp. * °F	600	800	1000

*Based on a minimum hot hardness of Rc 57 after long-term soaking (500-1000 hrs.) at temperature.

AL67T063

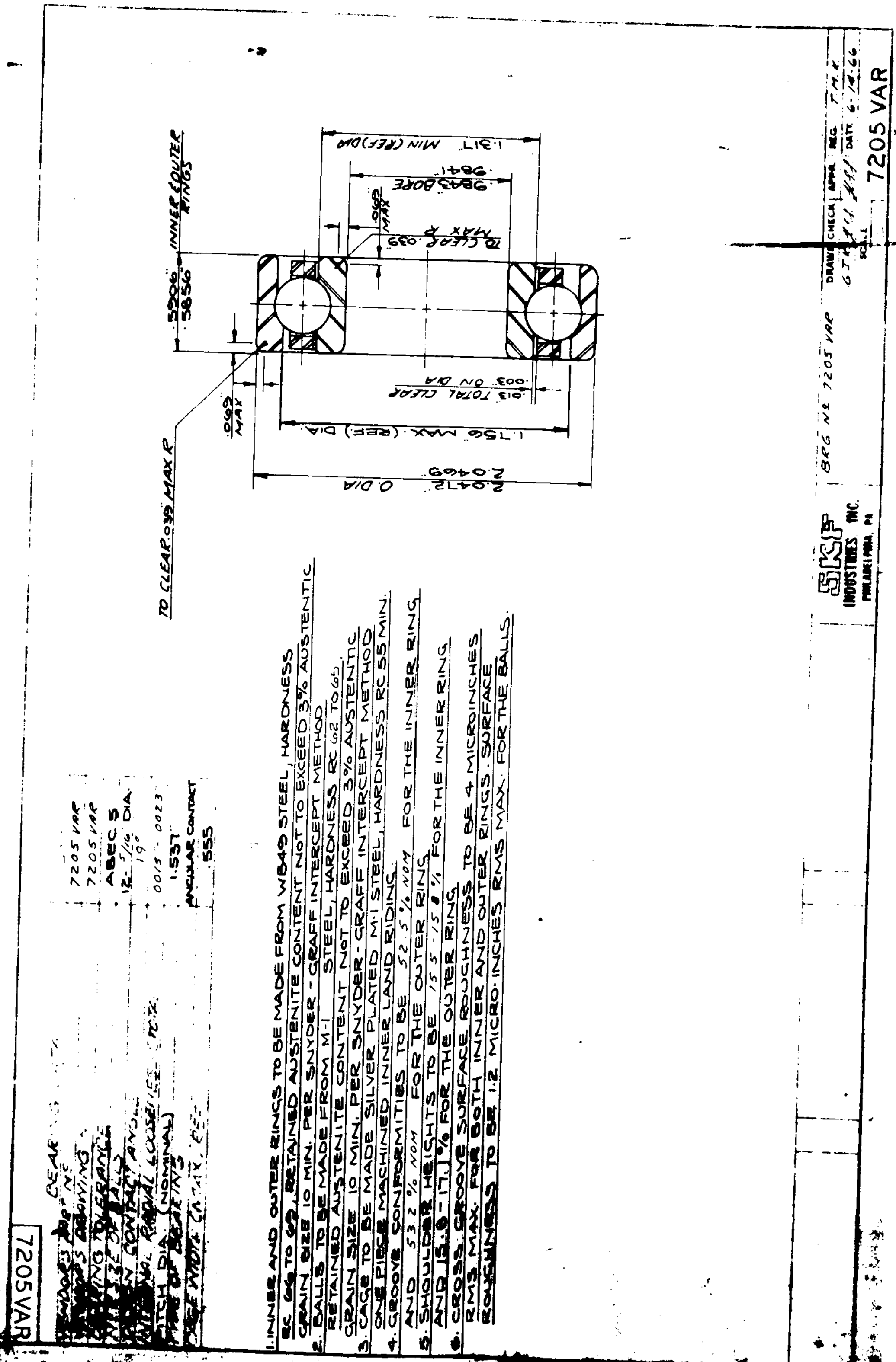
ENCLOSURE 5

ASSEMBLY DRAWING AND SPECIFICATIONS FOR TEST BEARING NO. 7205 VAK
HAVING BLACK-OXIDE COATED WB49 RINGS AND M-1 BALLS



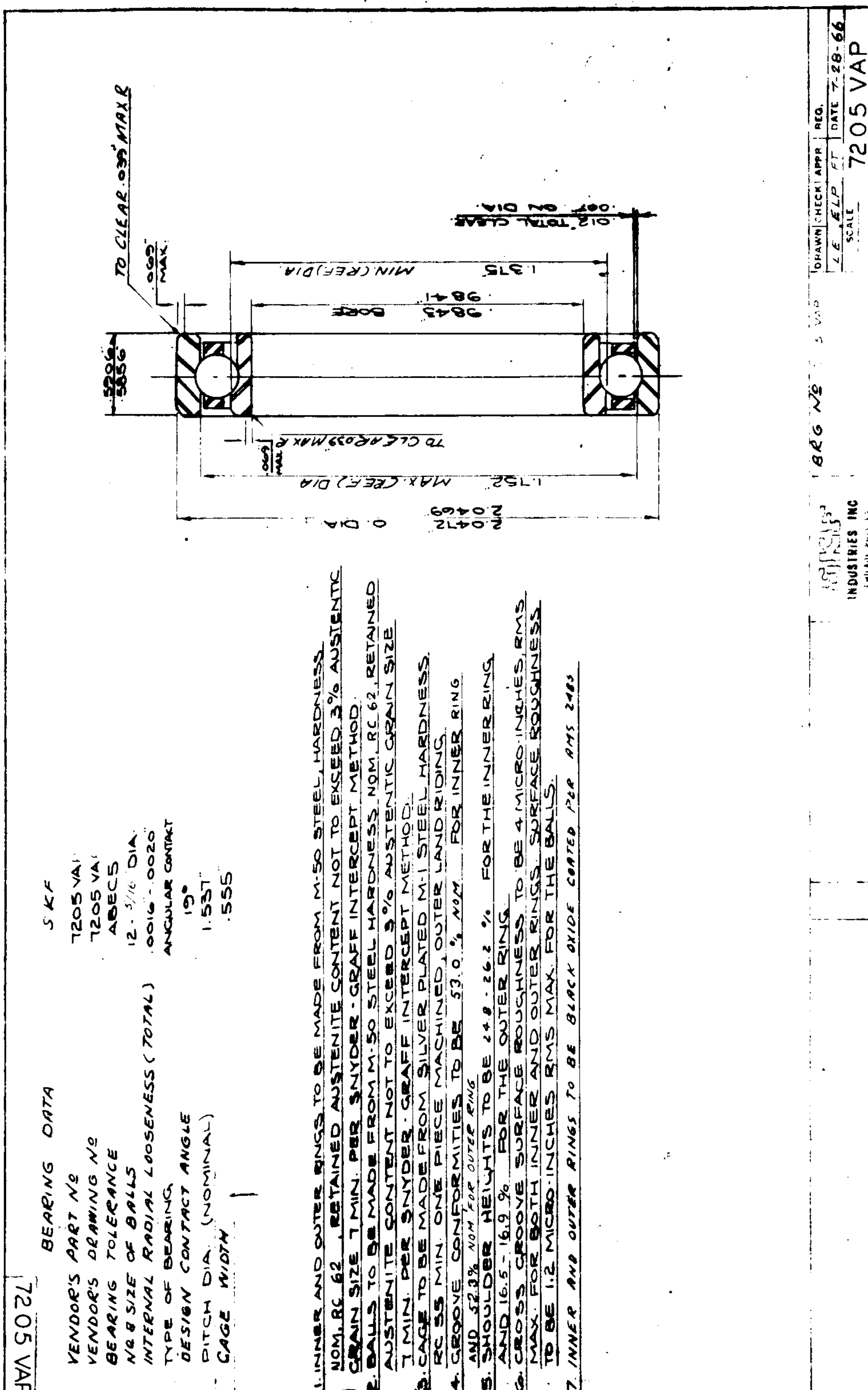
ENCLOSURE 6

ASSEMBLY DRAWING AND SPECIFICATIONS FOR TEST BEARING NO. 7205 VAR
HAVING UNCOATED WB-49 RINGS AND M-1 BALLS



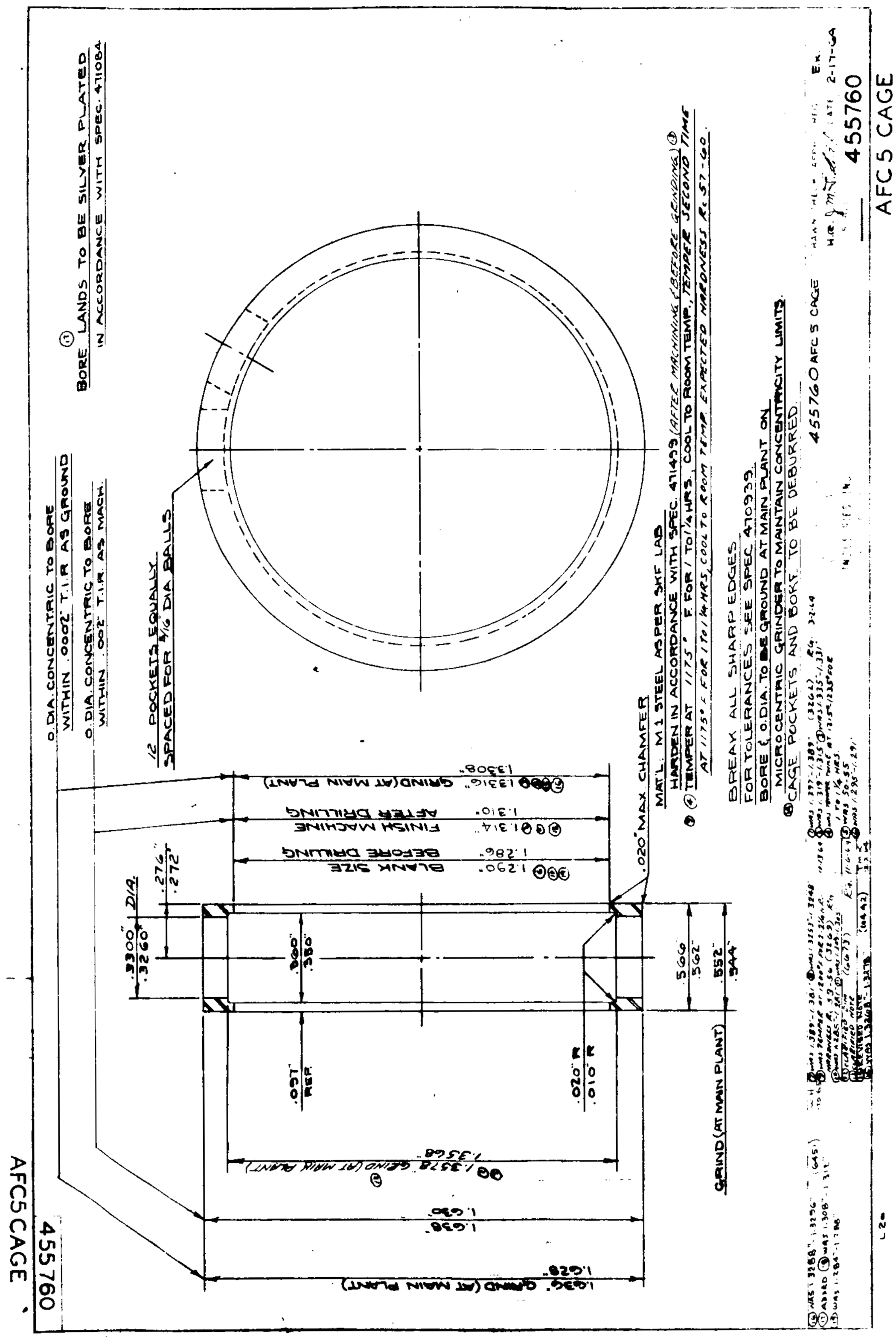
ENCLOSURE 7

ASSEMBLY DRAWING AND SPECIFICATIONS FOR TEST BEARING NO. 7205 VAP
HAVING BLACK OXIDE COATED M-50 RINGS AND BALLS



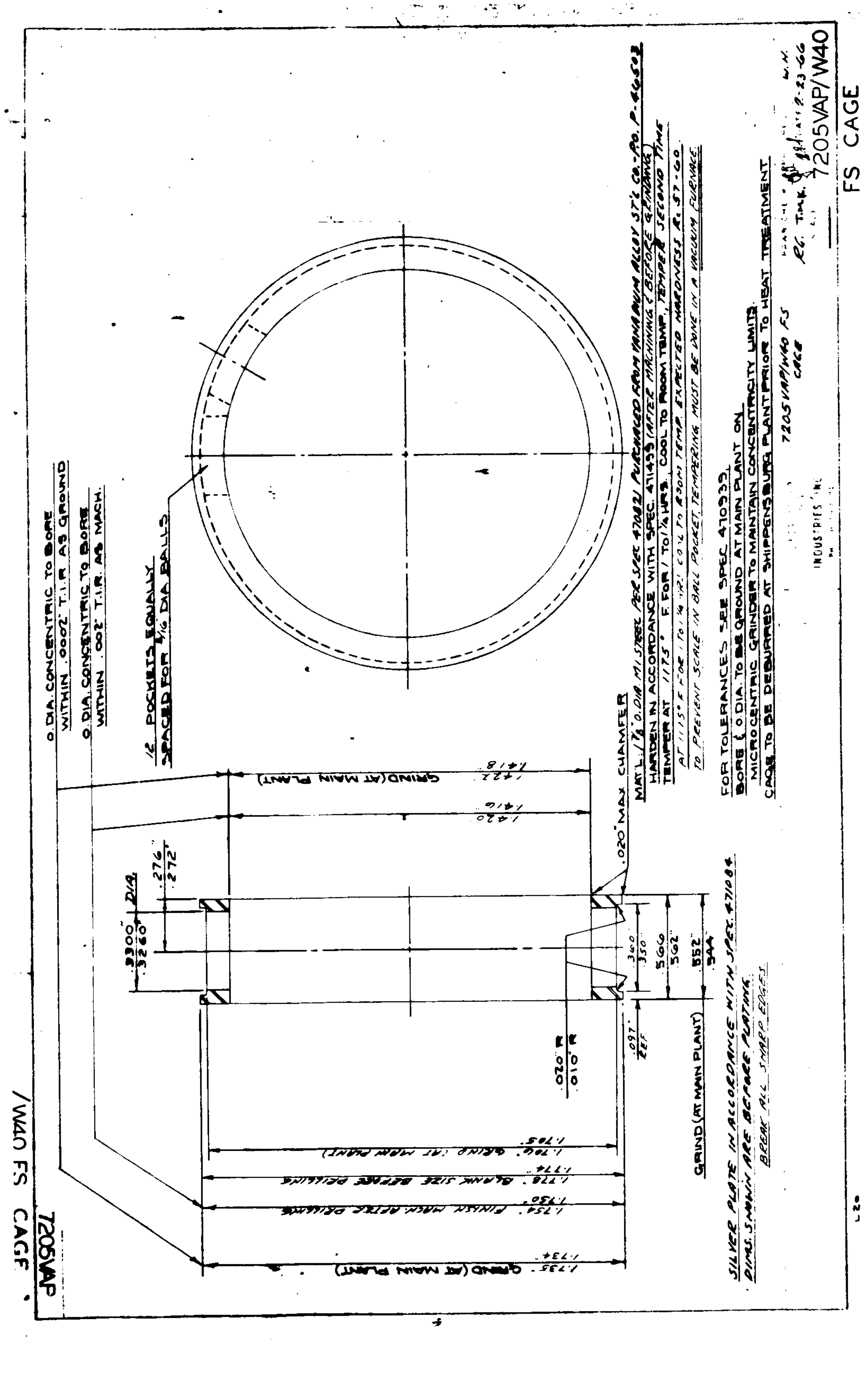
ENCLOSURE 8

INNER-RING-GUIDED SILVER PLATED M-1 STEEL CAGE
FOR USE WITH 7205 VAK AND 7205 VAR BRGS.



ENCLOSURE 9

OUTER-RING-GUIDED SILVER-PLATED M-1
STEEL CAGE FOR USE WITH 7205 VAP BRGS.



F-4136A - R50 - 17.00 X 22.00

ENCLOSURE 10

HARDNESS MEASUREMENTS ON TEST BEARING RINGS AND BALLS

Rockwell C hardness tests were conducted on all test bearing components employing the general requirements of standard methods ASTM Designations: E18-65 for hardening of metallic materials and E29-60T for Designating Significant Places in Specified Limiting Values.

A minimum of one inner ring and one outer ring per heat treatment lot were hardness tested at three locations on the face of the rings. Balls were checked in the center of a ground flat on four or five balls per heat treatment lot. The Rockwell testing machines are checked with "Rockwell" test blocks made and standardized in the testing laboratory of the Wilson Mechanical Instrument Division, American Chain and Cable Company. Rockwell C results are reported below to the nearest 0.5 value.

		Rockwell C Hardness		
Bearing No.	Material Grade	Inner Ring	Outer Ring	Balls
7205 VAK & VAR	WB49 rings	69.0	69.0	—
7205 VAK	M-1 balls	—	—	64.5
7205 VAR	M-1 balls	—	—	64.0
7205 VAP	M-50	63.5	63.5	64.0

ENCLOSURE 11

DIMENSIONAL MEASUREMENTS DATA ON 7205 VAK AND 7205 VAR BEARINGS BEFORE TESTING

Bearing No.	Serial No.	Average Outside Diameter, MM	Average Bore Diameter, MM	Contact Angle,* Degrees	Average Radial Looseness, Microns	Average Radial Cage Play, Inches	Taper, Microns O.R.	Taper, Microns I.R.	Out of Roundness Microns O.R.	Out of Roundness Microns I.R.
7205 VAK	101	51.997	24.997	16.5	47	.008	0.0	0.0	2.0	2.0
	102	51.997	24.9982	16.0	50	.007	0.0	1.5	2.0	2.0
	103	51.9962	24.997	15.4	47	.007	0.7	1.0	3.0	1.0
	104	51.9975	24.9982	19.1	49	.007	0.0	1.5	1.0	3.0
	105	51.9972	24.9962	15.4	49	.008	0.5	0.5	2.0	2.0
	106	51.994	24.9975	16.0	42	.008	3.0	0.0	2.0	1.0
	107	51.9967	24.999	16.5	44	.007	0.5	2.0	3.0	2.0
	108	51.9975	24.9975	16.0	46	.008	1.5	2.0	3.0	1.0
	109	51.994	24.9987	16.0	47	.008	0.0	0.5	2.0	3.0
	110	51.9955	24.997	16.5	46	.008	1.0	1.0	2.0	3.0
	201	51.9938	24.9998	16.0	48	.007	0.5	1.0	2.0	3.0
	202	51.9965	25.0000	16.5	49	.007	1.0	0.0	2.0	2.0
	203	51.9980	24.9968	16.5	48	.008	2.0	0.5	2.0	2.0
	204	51.9993	24.9978	16.0	48	.007	0.5	0.5	2.0	4.0
	301	51.9970	24.9975	15.3	42	.007	1.0	2.0	3.0	3.0
	302	51.9950	24.9980	16.5	45	.007	1.0	2.0	1.0	2.0
7205 VAR	401	51.9939	-	19.8	58	.007	-	-	-	-
	402	51.9989	-	18.5	53	.008	-	-	-	-
	403	51.9939	-	19.0	51	.007	-	-	-	-
	404	51.9987	-	17.0	50	.007	-	-	-	-
	405	51.9913	-	18.5	55	.008	-	-	-	-
	406	52.001	-	18.0	52	.008	-	-	-	-
	407	51.9987	-	15.3	51	.008	-	-	-	-
	408	51.9913	-	18.0	53	.008	-	-	-	-
	409	51.9975	24.9982	15.8	39	.008	0.0	0.5	1.0	3.0
	410	51.9975	24.9975	16.4	40	.008	1.0	0.0	2.0	1.0
	411	52.001	24.9987	16.4	46	.008	0.0	0.5	2.0	2.0
	412	52.000	24.998	15.8	46	.009	0.0	1.0	2.0	3.0
	413	51.998	24.997	15.3	45	.008	0.0	2.5	2.0	2.0
	414	51.9975	24.998	14.7	46	.008	1.5	0.0	2.0	2.0
	415	52.000	24.999	15.3	47	.008	1.0	1.0	2.0	1.0
	416	51.9977	24.9965	15.8	44	.008	0.5	1.0	2.0	2.0
	417	51.9975	24.9975	15.3	43	.008	0.0	0.0	1.0	1.0
	418	52.001	24.9980	13.4	42	.008	0.0	1.0	2.0	1.0
	419	52.000	24.9975	14.0	41	.008	1.0	0.0	1.0	1.0
	420	51.996	24.999	14.7	40	.008	0.0	1.0	2.0	1.0
	421	51.9985	24.999	15.3	40	.008	1.0	0.0	2.0	2.0
	422	51.9975	24.9975	14.7	40	.008	0.0	0.0	3.0	1.0
	423	51.9980	24.997	14.7	39	.008	0.0	0.0	2.0	2.0
	424	52.0000	24.9975	15.8	39	.008	1.0	0.0	1.0	1.0
	425	51.9985	24.999	14.0	38	.008	1.0	1.0	2.0	1.0
	426	51.9952	24.9972	14.0	37	.008	0.5	0.5	2.0	3.0
	427	51.9985	24.998	14.7	37	.008	0.0	0.0	1.0	2.0
	428	51.9965	24.9995	14.7	37	.008	2.0	0.0	1.0	3.0
	429	51.9962	24.997	14.7	37	.008	0.5	1.0	3.0	1.0
	430	51.9995	24.9977	14.0	37	.008	1.0	1.5	2.0	2.0

*These measured values are all lower than the contact angle of about 19° calculated from measured looseness and cross-groove radius. Experience shows that contact angle measurements are very sensitive to minor groove geometry differences.

Notes:

1) Approximately 15% random sample of cross-groove surface roughness indicates the following:

	Microinches, RMS
Outer Ring	
Inner Ring	2.1 - 2.5
Outer Ring	2.9 - 3.8

2) All 7205 VAR bearings (No. 401 to 430) were measured for cross-groove radius and were within the following limits:

Inner Ring	4.139/4.188 mm
Outer Ring	4/196/4.249 mm

7205 VAP BEARING MEASUREMENTS

	Bearing No.	Groove Radii (mm) Inner	Groove Radii (mm) Outer	Contact Angle (degrees)	Radial Looseness (μin)	Surface Roughness (μin AA) Inner	Surface Roughness (μin AA) Outer	Taper (μin) Inner	Taper (μin) Outer	Out of Roundness (μm) Inner	Out of Roundness (μm) Outer	Bore (mm)
1)	7	4.187	4.171	23.0	57			3/4	0	1/2	1	24.998
2)	10	4.223	4.176	24.6	55	1.53	1.95	1	1	1	1	24.998
3)	13	4.231	4.180	23.8	62			3/4	1	1	1	24.998
4)	14	4.221	4.181	25.6	57			1/2	0	1/2	1	24.998
5)	16	4.228	4.172	24.2	59	1.38	3.16	1/2	1	1/2	1	24.998
6)	17	4.217	4.184	22.6	49			1/4	2	1	1	24.998
7)	18	4.212	4.178	26.0	59			1/2	0	1	1	24.999
8)	19	4.208	4.216	23.8	58			1/2	0	1/2	1	24.999
9)	20	4.210	4.200	22.2	52	1.43	1.85	1/2	0	1/2	1	24.999
10)	21	4.211	4.200	23.1	55			1/2	1	1	1	24.999
11)	25	4.195	4.170	24.5	55	1.50	1.73	1/2	1	1/2	2	24.999
12)	26	4.203	4.175	24.8	52			1/2	0	1/2	1	24.998
13)	29	4.242	4.176	23.8	56	1.58	1.98	1/2	0	1/2	1	24.998
14)	30	4.231	4.176	24.4	50			1-1/4	1	1	1	24.997
15)	33	4.222	4.175	23.1	51			1/2	1	1	1	24.999
16)	34	4.214	4.169	23.0	59	1.50	1.71	1/4	0	1/2	1	24.999
17)	35	4.212	4.194	22.0	59			1/2	0	1/2	1	24.999
18)	43	4.230	4.191	22.0	56							
19)	44	4.235	4.171	23.1	52							
20)	48	4.238	4.176	23.1	58							
21)	49	4.227	4.182	23.8	57							
22)	55	4.213	4.187	23.8	51							
23)	73	4.214	4.177	24.4	55							
24)	74	4.196	4.184	24.8	49							
25)	76	4.207	4.189	25.1	56							
26)	78	4.203	4.194	25.1	55							
27)	91	4.211	4.168	24.8	57							
28)	92	4.200	4.181	23.1	60							
29)	93	4.205	4.194	23.1	58							
30)	97	4.205	4.184	23.1	60							
31)	98	4.193	4.186	24.1	60							
32)	101	4.216	4.189	22.3	53							
33)	104	4.197	4.189	23.1	60							
34)	105	4.202	4.179	24.1	64							
35)	116	4.195	4.203	23.1	48							
36)	131	4.202	4.171	22.7	63							
37)	134	4.186	4.172	23.1	56							
38)	137	4.206	4.186	23.7	61							
39)	140	4.195	4.199	23.7	53							
40)	142	4.186	4.196	21.3	54							
41)	143	4.191	4.199	22.0	54							
42)	144	4.197	4.204	22.3	59							
43)	145	4.243	4.198	22.7	60							
44)	149	4.240	4.178	22.3	62							
45)	154	4.205	4.179	25.1	60							
46)	158	4.241	4.187	23.4	57							
47)	165	4.217	4.180	24.4	52							
48)	197	4.198	4.179	23.4	59							
49)	205	4.226	4.206	23.8	68							
50)	207	4.212	4.185	24.1	48							
51)	208	4.219	4.177	24.1	57							
52)	213	4.185	4.175	24.1	53							
53)	217	4.197	4.228	22.0	52							
54)	235	4.186	4.190	23.1	46							

ENCLOSURE 13

PROPERTIES OF MOBIL XRM 177F LUBRICANT*
(compared with previous lots of XRM 109F base-stock)

Property		XRM 109F (initial lot)	XRM 109F-1 (lot No. 1)	XRM 177F (same as XRM 109F-2)
Viscosity, cs, at	400°F	4.92	6.51	5.82
	210°F	31.95	43.45	39.85
	100°F	314.1	454.3	442.6
	0°F	-	-	37,610
	-20°F	96,099	-	-
	-40°F	> 99,000	-	-
Pour Point, °F		-40	-60	< -35
Flash Point, °F		530	450	515
Fire Point, °F		580	545	600
Autogenous Ignition Point, °F		775	755	830
Neutralization No.		-	-	0.11 (0.05 for XRM 109F-2)
Bromine No.		-	-	0.1
Carbon Residue, %		-	-	< 0.01
Volatility, 6-1/2 hrs. @ 500°F, %		15	14.2	-
Molecular Weight		-	1,430	-
Vapor Pressure, Isoteniscope, microns at	250°F		74	
	300°F		115	
	350°F		165	
	400°F		230	
Dielectric Constant, 1000 cps at	180°F			2.12
	260°F			2.08
	360°F			2.03
(extrapolated)	600°F			1.91

Four-Ball Wear Test Data*

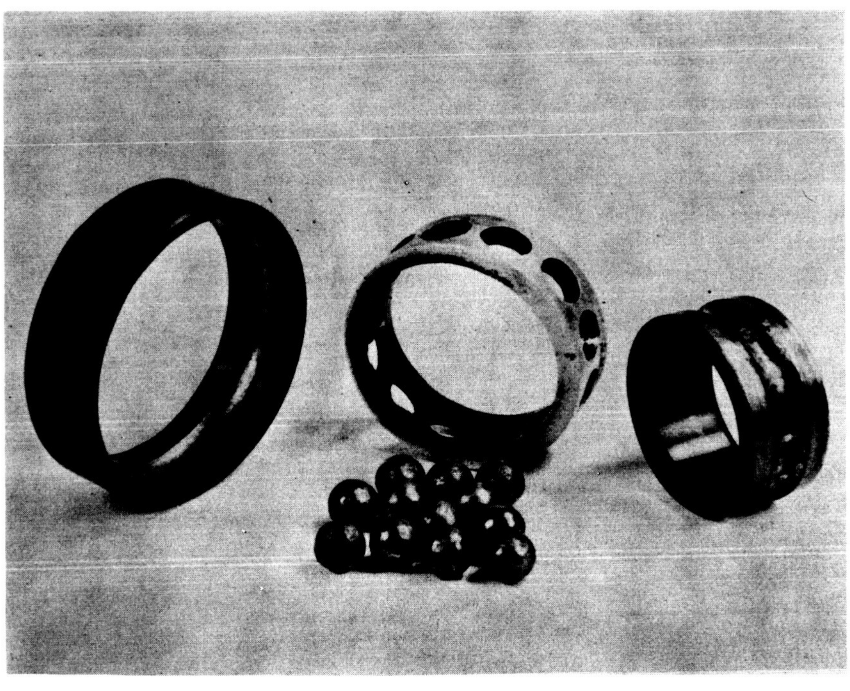
Sample	Time	Temp., °F	Speed, rpm	Load, kg	Average Wear Scar Diameter, mm
XRM 109F-2	1 Hour	167	1800	10	0.458
XRM 177F-2	1 Hour	167	1800	10	0.240
XRM 109F-2	1 Hour	400	600	10	0.373
XRM 177F-2	1 Hour	400	600	10	0.278

*Courtesy of Mobil Oil Company

ENCLOSURE 14

TYPICAL SMEARING FAILURE OF BLACK-OXIDE COATED WB-49 7205 VAK BEARING

INNER RING GROOVE



BEARING NO. 104 FROM TEST NO. II-2

ENCLOSURE 15

ENDURANCE OF CVM WB-49 7205 VAK BEARINGS (BLACK OXIDE COATED)

THRUST LOAD = 459LBS.(C/P = 6.2)   SPEED = 43,000 RPM   LUBRICANT-MOBIL XRM 177F*

TEST RUN NO.	BRG. NO.	CAGE BORE WEAR MILS.	AVG. BRG. TEMP.°F	AVG. SUMP TEMP.°F	LUBRICATION DISTRESSED ELEMENTS	PARTS FAILED	LIFE 10^6 REVS.
11-6	201	34.0	-	-	I.R. O.R. AND BALLS SMEARED	I.R. O.R. AND BALLS	0.5
	202	2.0	-	-	NONE	NONE	
11-9	*301	9.8	-	-	NONE	NONE	1.0
	*302	25.3	-	-	I.R.,O.R. AND BALLS SMEARED	I.R.,O.R. AND BALLS	
11-7	203	48.0	572	537	I.R. O.R. AND BALLS SMEARED	I.R.,O.R. AND BALLS	1.7
	204	13.5	605		NONE	NONE	
11-4	107	9.2	618	516	I.R.,O.R. SLIGHTLY GLAZED BALLS-2 FLAKED	I.R. O.R. AND BALLS	2.6
	108	37.7	582		I.R.O.R. AND BALLS SMEARED	I.R.,O.R. AND BALLS	
11-3	105	7.2	545	615**	NONE	NONE	3.4
	106	46.2	614		I.R.,O.R. AND BALLS SMEARED	I.R.,O.R. AND BALLS	
11-2	103	4.8	576	541	NONE	NONE	6.7
	104	41.7	592		I.R.,O.R. AND BALLS SMEARED	I.R.,O.R. AND BALLS	
11-5	109	5.0	607	603**	NONE	NONE	19.0
	110	65.0	585		I.R.-GLAZED AND FLAKED.O.R. GLAZED AND PITTED	I.R., AND O.R.	
11-1	101	13.0	592	576	I.R., O.R. GLAZED AND FLAKED BALLS 3 FLAKED	I.R.,O.R. AND BALLS	23.9
	102	4.2	585		I.R.,O.R. AND BALLS SMEARED	I.R.,O.R. AND BALLS	

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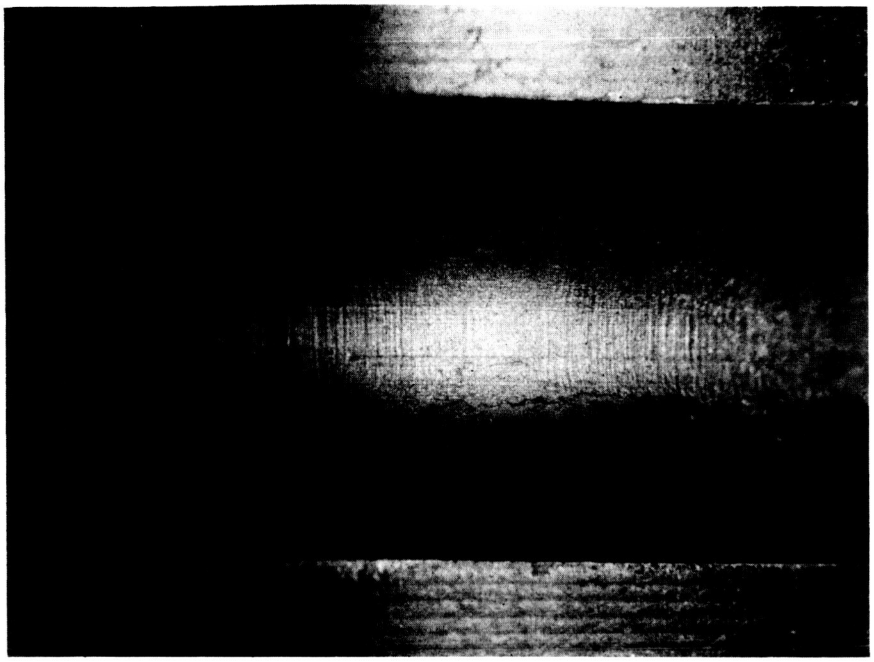
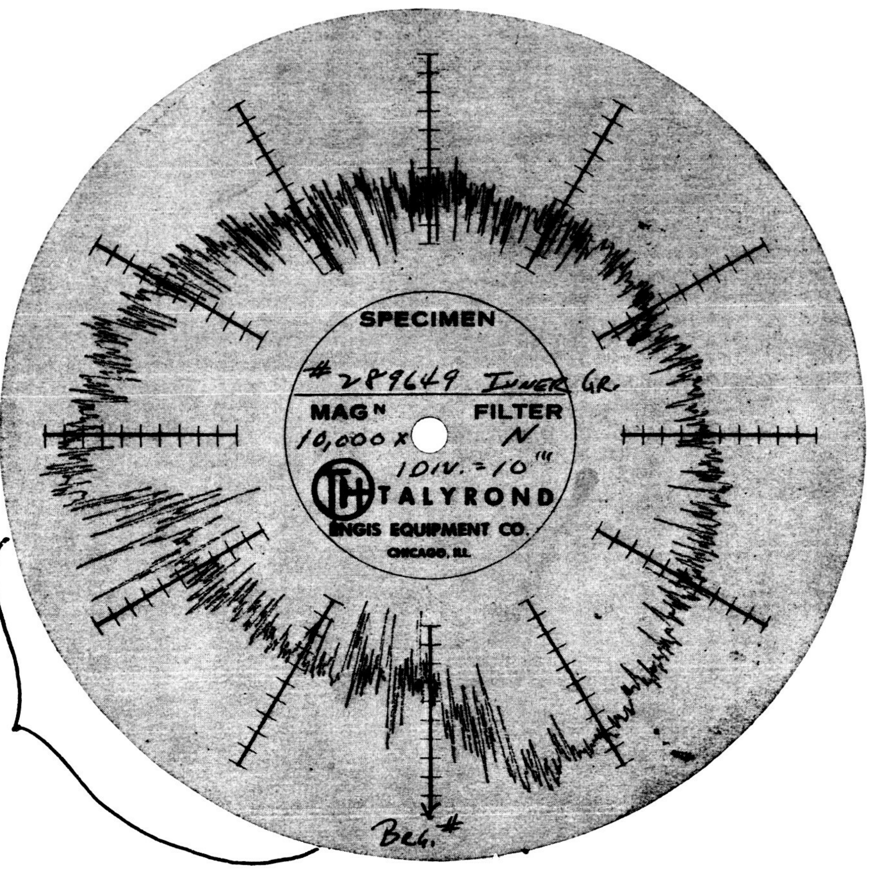
* THESE BEARINGS WERE TESTED USING ESSO TURBO OIL 35.

** THESE VALUES ARE NOT BELIEVED TO BE RELIABLE.

WB-49 STEEL SURFACE OF NEW 7205 VAK BEARING SHOWING ATTACK OF BLACK OXIDE COATING



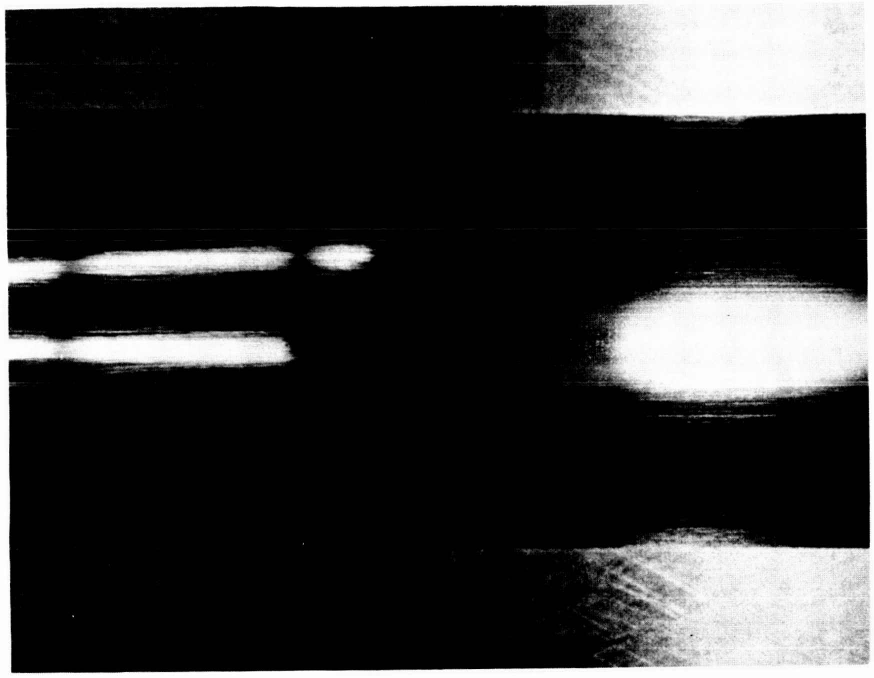
NEW INNER RING GROOVE WITH THE COATING REMOVED FROM THE AREA SHOWN ABOVE



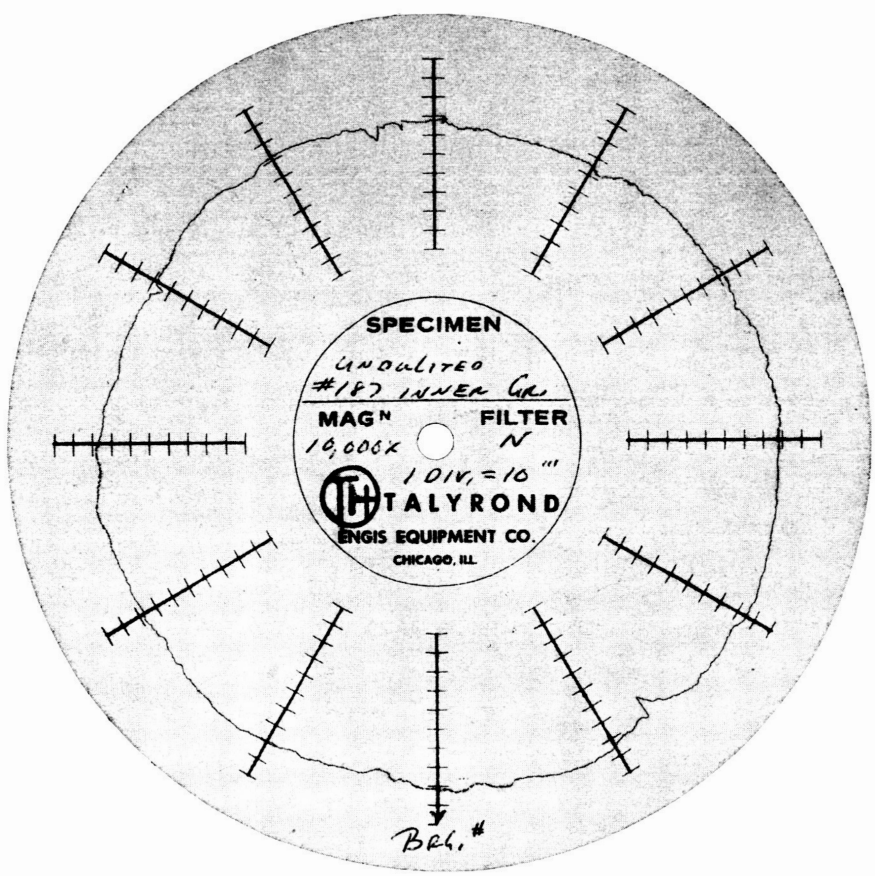
COATING REMOVED IN THIS AREA

CIRCUMFERENTIAL SURFACE TRACE OF NEW BLACK OXIDE COATED WB-49 STEEL INNER RING WITH THE COATING REMOVED FROM THE AREA SHOWN ABOVE

WB-49 STEEL SURFACE OF UNCOATED NEW 7205 VAR BEARING



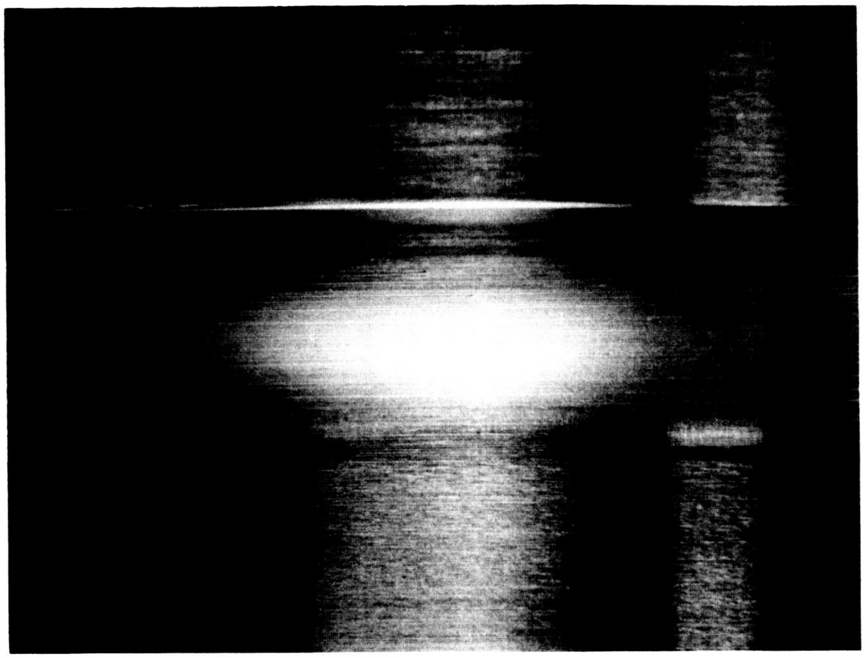
NEW INNER RING GROOVE



CIRCUMFERENTIAL SURFACE TRACE OF NEW UNCOATED WB-49 STEEL INNER RING

ENCLOSURE 18

M-50 STEEL SURFACE UNDER BLACK
OXIDE COATING ON NEW INNER RING



NEW INNER RING GROOVE WITH COATING REMOVED

ENCLOSURE 19

ENDURANCE OF CVM WB-49 7205 VAR BEARINGS (UNCOATED)

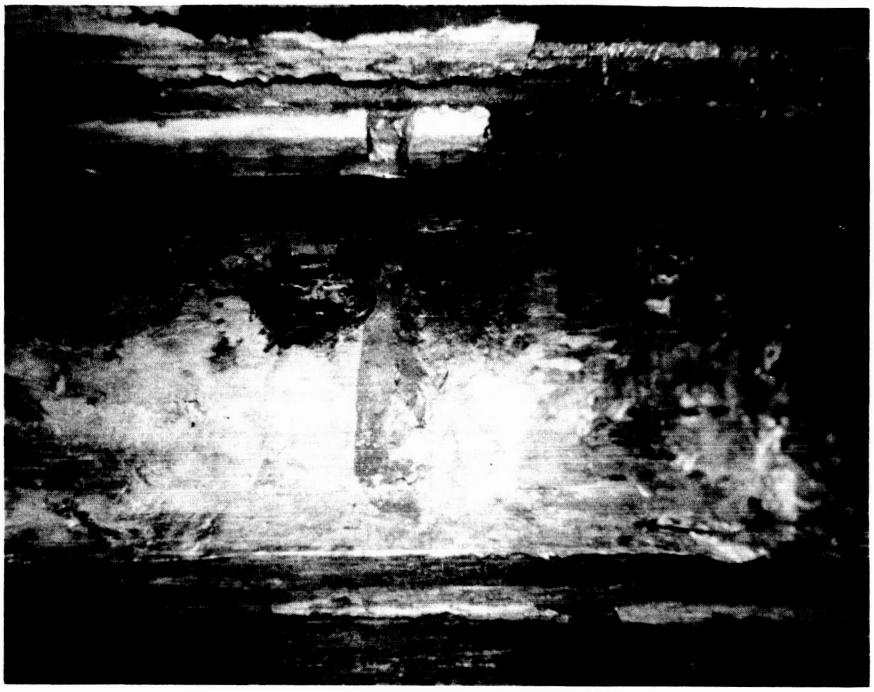
THRUST LOAD = 459 LBS.(C/P = 6.2)   SPEED = 43,000 RPM   LUBRICANT - MOBIL XRM-177F

TEST RUN NO.	BRG. NO.	CAGE BORE WEAR MILS.	AVG. BRG. TEMP. °F	AVG. SUMP TEMP. °F	LUBRICATION DISTRESSED ELEMENTS	PART(S) FAILED	LIFE 10^6 REVS.
11-19	419 420	43.8 3.3	574 586	537	I.R., O.R., BALLS SMEARED NONE	I.R., O.R., BALLS NONE	46.2
11-12	405 406	7.6 <0.1	600 601	600*	NONE I.R., O.R., BALLS SMEARED	NONE I.R., O.R. AND BALLS	70.7
11-18	417 418	<0.1 39.5	601 587	541	NONE I.R., O.R., AND BALLS SMEARED	NONE I.R., O.R. AND BALLS	125.6
11-10	401 402	3.5 4.5	607 557	600*	NONE NONE	NONE NONE	465 465
11-11	403 404	4.0 4.2	594 602	588	NONE NONE	NONE NONE	465 465
11-13	407 408	4.0 1.7	592 604	592	NONE NONE	NONE NONE	465 465
11-14	409 410	2.1 0.2	579 598	536	NONE NONE	NONE NONE	465 465
11-15	411 412	0.5 <0.1	594 595	546	NONE NONE	NONE NONE	465 465
11-16	413 414	<0.1 <0.1	600 565	574	NONE NONE	NONE NONE	465 465
11-17	415 416	<0.1 3.5	600 590	579	NONE NONE	NONE NONE	465 465
11-20	421 422	<0.1 0.2	598 593	534	NONE NONE	NONE NONE	465 465
11-21	423 424	1.5 0.7	599 578	573	NONE NONE	NONE NONE	465 465
11-22	425 426	4.2 4.0	587 588	615*	NONE NONE	NONE NONE	465 465
11-23	427 428	0.5 <0.1	601 585	541	NONE NONE	NONE NONE	465 465
11-24	429 430	5.2 <0.1	597 594	577	NONE NONE	NONE NONE	465 465

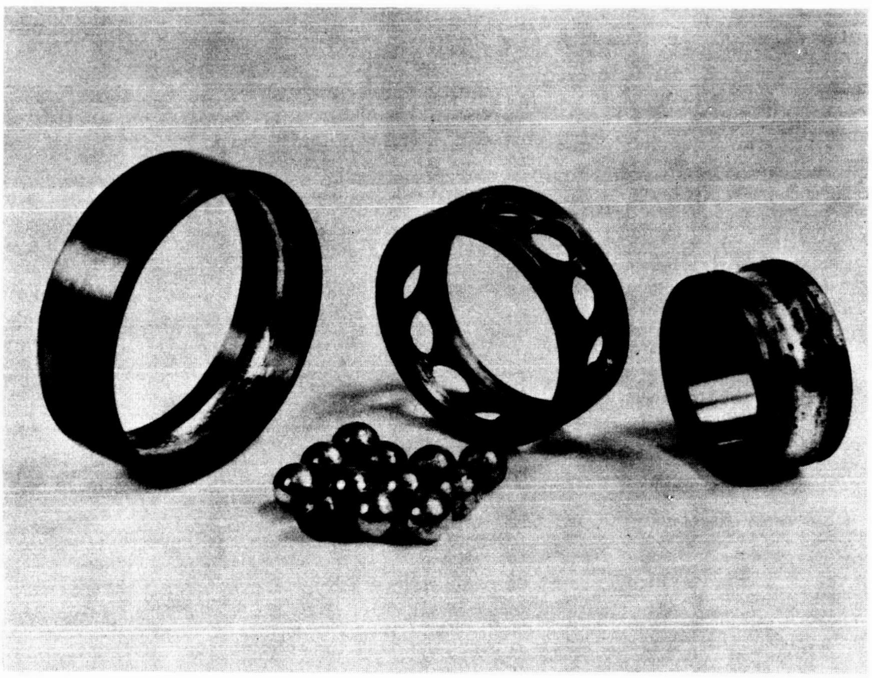
* THESE VALUES ARE NOT BELIEVED TO BE RELIABLE.

ENCLOSURE 20

SMEARED 7205 VAG BEARING AFTER TESTING AT 600°F



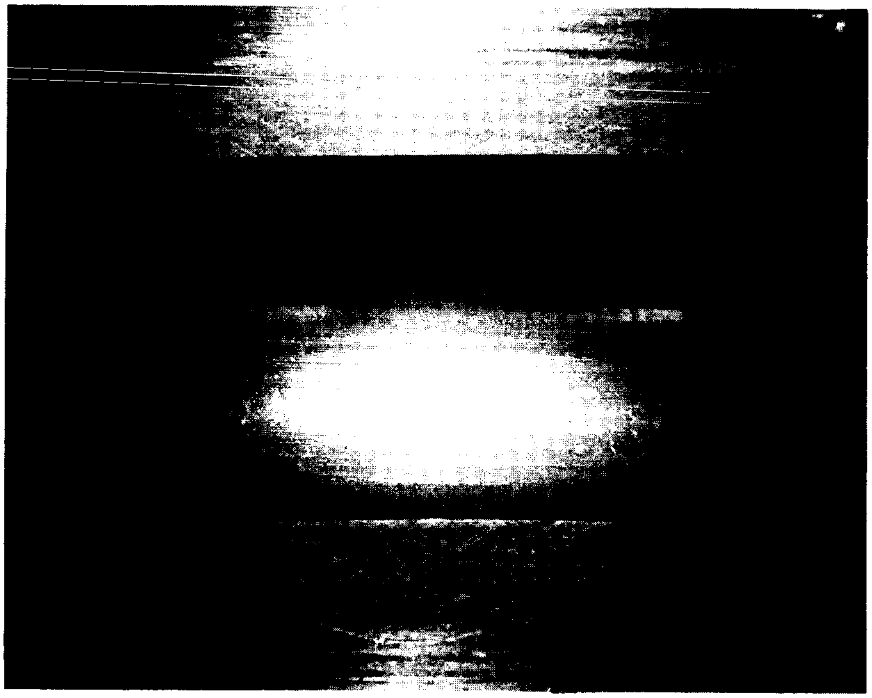
SMEARED INNER RING GROOVE



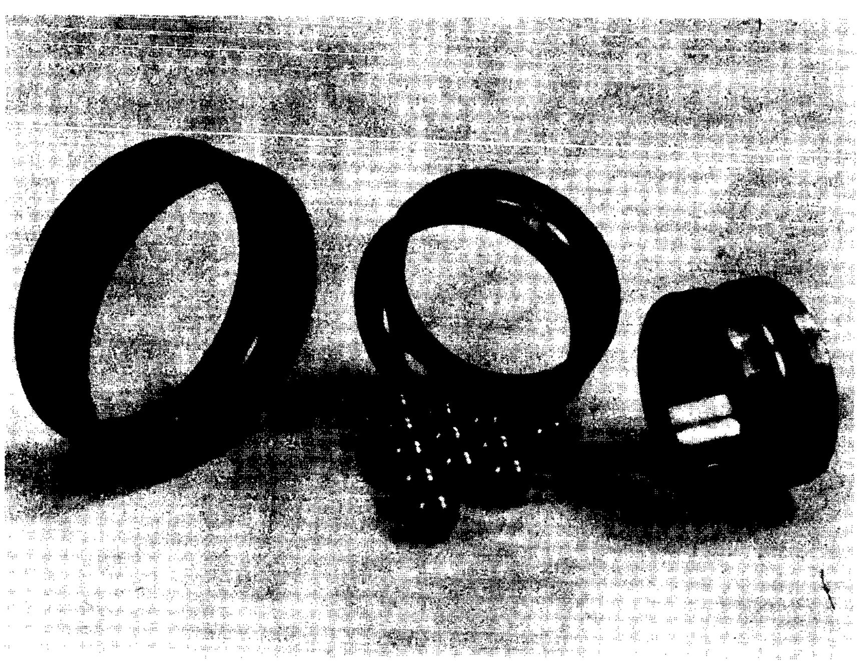
BEARING NO. 194130 TEST RUN NO. III-15

ENCLOSURE 21

TYPICAL UNFAILED 7205 VAR BEARING



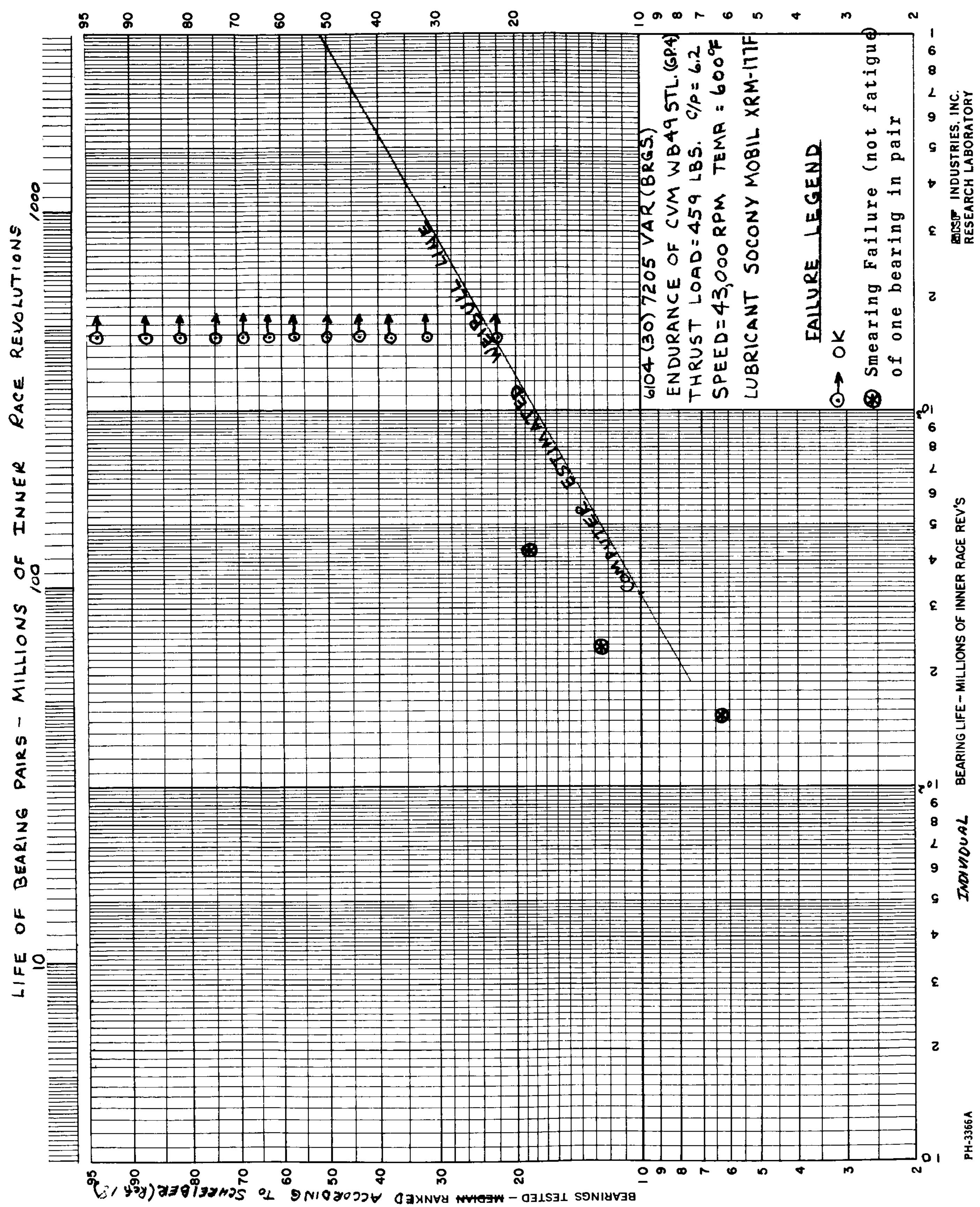
INNER RING GROOVE



BEARING NO. 108429 TEST RUN NO. II-24

ENCLOSURE 22

WEIBULL PLOT OF 7205 VAR FAILURE DATA

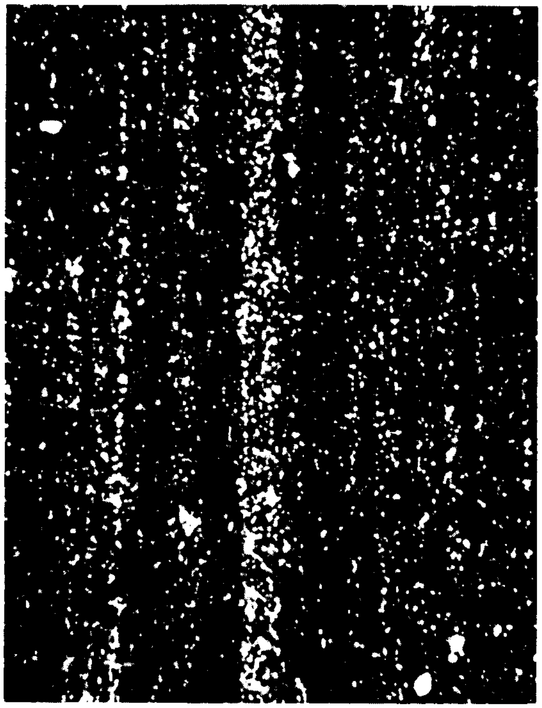


ENCLOSURE 23

STRUCTURE OF WB-49 BEARING STEEL

250X

1000X



Structure of WB-49 Steel Ball From a 6309 Ball Set Which Showed 4 Times AFBMA Computed Bearing Life (8)

Structure of WB-49 Steel 6309 Ring Which Showed 9 Times AFBMA Computed Fatigue Life (8)

ENCLOSURE 24

COMPUTED DYNAMIC CHARACTERISTICS OF TEST BEARINGS

Test Conditions

Speed	43,000 rpm
Thrust Load	459 lbs.
Temperature	600 °F

Computed Operating Parameters	7205 VAR Bearings With Mean Looseness	7205 VAK Bearings Min. Looseness	7205 VAK Bearings Max. Looseness
Inner ring contact angle, degrees	23.4	19.9	24.5
Outer ring contact angle, degrees	17.7	15.5	18.1
Ball axis orientation angle, degrees	14.8	12.9	15.1
Axial bearing deflection, in.	0.00187	.00262	.00167
Inner semi-major contact axis, in.	0.03834	.03661	.03442
Inner semi-minor contact axis, in.	0.00456	.00498	.00471
Outer semi-major contact axis, in.	0.03543	.03785	.03607
Outer semi-minor contact axis, in.	0.00638	.00661	.00628
Ball centrifugal force, lbs.	29.8	30.6	31.2
Normal inner ring ball load, lbs.	92.0	108.1	88.0
Normal outer ring ball load, lbs.	119.8	137.2	116.9
Maximum inner ring contact stress, kpsi	251.3	282.9	259.1
Maximum outer ring contact stress, kpsi	252.7	261.9	246.1
Cage Speed, rpm	17,350	17,267	17,430
Ball rolling speed, rpm	85,826	83,590	84,379
Ball spinning speed, rpm	17,540	14,106	18,590
Ball gyroscopic moment, in.-lbs.	0.57	.52	.62
Spin-to-roll ratio on inner	0.20	.17	.22
Viscous heat generated, Btu/hr.	806.9	1194.3	806.9
Spinning heat generated, Btu/hr.	626.0	626.0	631.0
Total heat generated, Btu/hr.	3485.5	4787.7	3182.2
Minimum friction coefficient required to prevent gyro slip	0.017	.013	.019
Bearing life (Lundberg-Palmgren), hrs.	56.2	32.0	55.6
Life of inner ring contact, hrs.	68.7	36.5	64.4
Life of outer ring contact, hrs.	244.2	199.5	317.7
EHD oil film thickness on inner ring for 2.5 cs viscosity lubricant, microinches	7.6	7.5	7.7

ENCLOSURE 25

ANALYSIS OF XRM 177F FLUID SAMPLES BEFORE AND AFTER 600°F TESTING

Property	New XRM 177F*	Used XRM 177F* (Test E-82) (8)
Kinematic Viscosity at 210°F, cs	39.63	49.55
Change	-	+25.0
Bromine No.	0.1	0.5
Carbon Residue	0.01	-

*Courtesy of Mobil Oil Company

ENCLOSURE 26

SUMMARY OF HIGH-TEMPERATURE BEARING ENDURANCE RESULTS

(7205 bearings at 43,000 rpm with N_2 blanket)

Bearing Steel	Lubricant	Temp. °F	Thrust Load Lbs.	No. Bearings Tested	No. Bearings Failed	Predominant Failure Mode	Bearing L10 Life, Mill. Revs. Calculated AFBMA	Calculated Computer	Max. Likelihood Estimated
M-1	Esso Turbo Oil 35	500	365	30	2	Smearing	480		248
M-1	Esso Turbo Oil 35	500	459	30	10	Spalling*	240	207	59
M-1	Mobil XRM-177F	600	459	10	0	None	240	207	> 500
WB-49	Mobil XRM-177F	600	459	30	3	Smearing	240	144	328

* With lubrication distress

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